

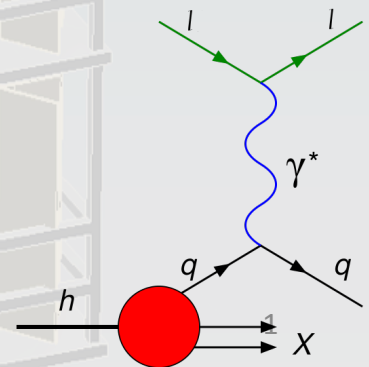
# From PHENIX to an EIC Detector

Built Around the BaBar Magnet and  
sPHENIX Calorimetry

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For PHENIX Collaboration

October 20-24, 2014, Beijing, China



# EIC Physics

Well developed and summarized in:

INT EIC report: [arXiv:1108.1713](#)

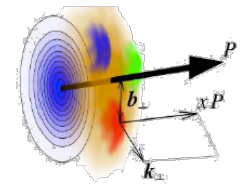
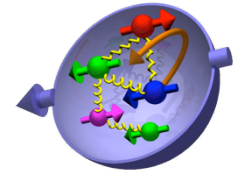
EIC White Paper: [arXiv:1212.1701](#)

Distribution of quarks and gluons and their spins in space and momentum inside the nucleon

Nucleon helicity structure

Parton transverse motion in the nucleon

Spatial distribution of partons and parton orbital angular momentum

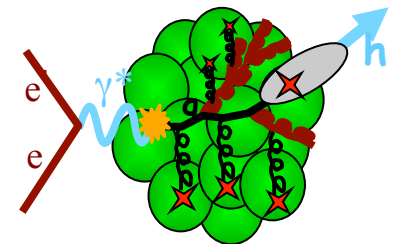


QCD in nuclei

Nuclear modification of parton distributions

Gluon saturation

Propagation/Hadronization in nuclear matter



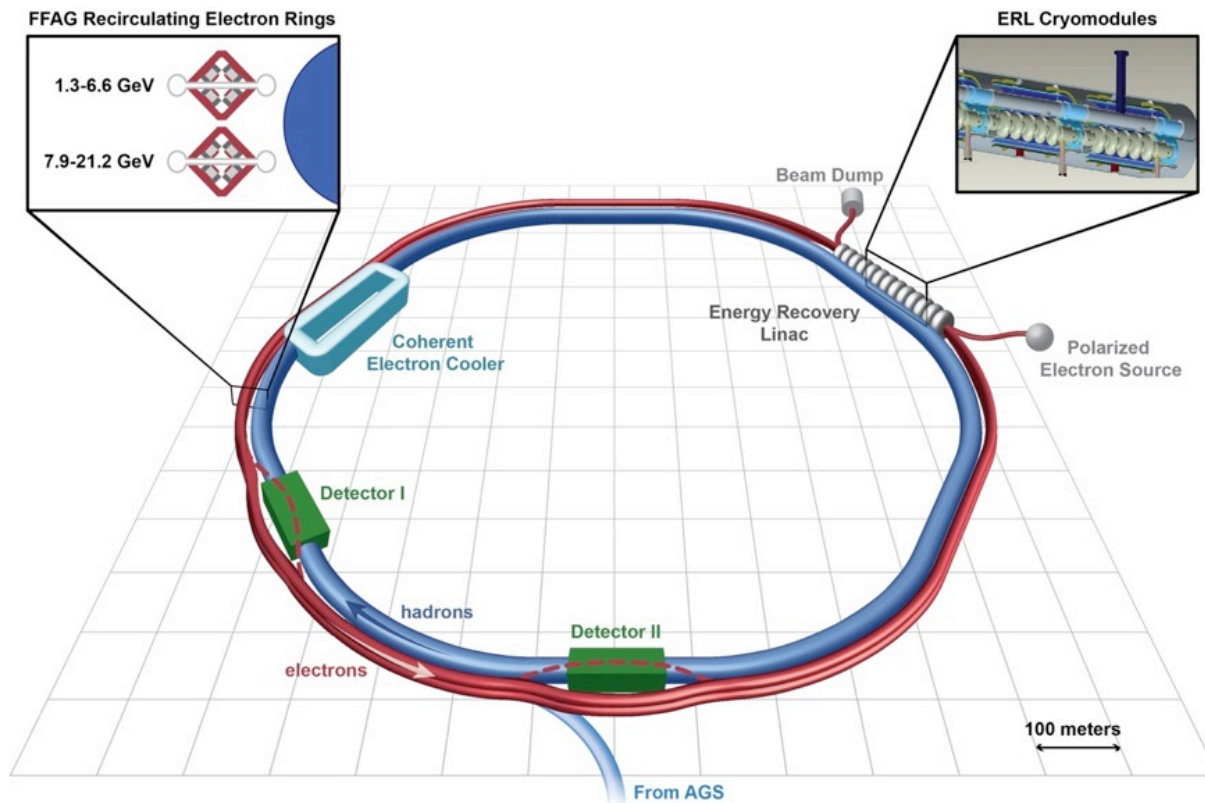
~~Weak interactions & beyond standard model~~

Require highest energy and lum. -> not for stage-1

# eRHIC (BNL, USA)

See M.Bai talk

ep/eA



In current design:

Energy:

Electron: 6.6–21.2 GeV

Proton: 25–250 GeV

Ions: 10–100 GeV

$\sqrt{s}$ : up to 145 GeV

Polarization:

Electrons: 80%

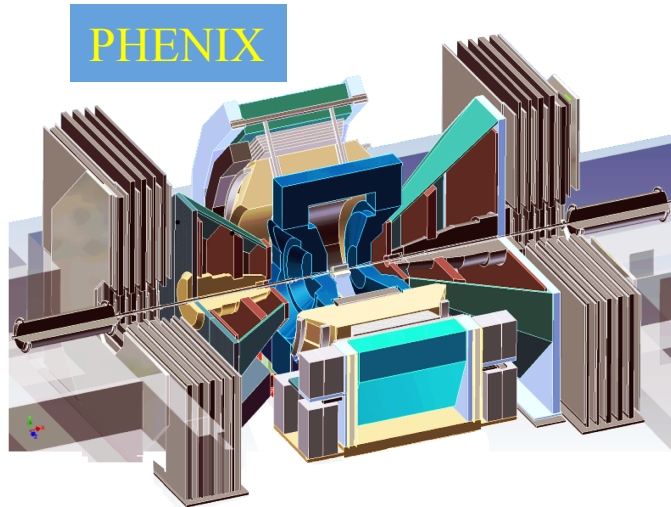
Protons and He3: 70%

Luminosity:

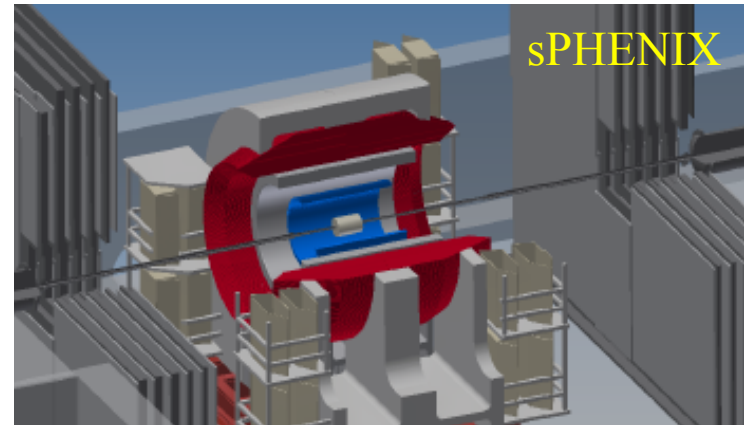
$>10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

... Still evolving

# PHENIX -> EIC Detector Path



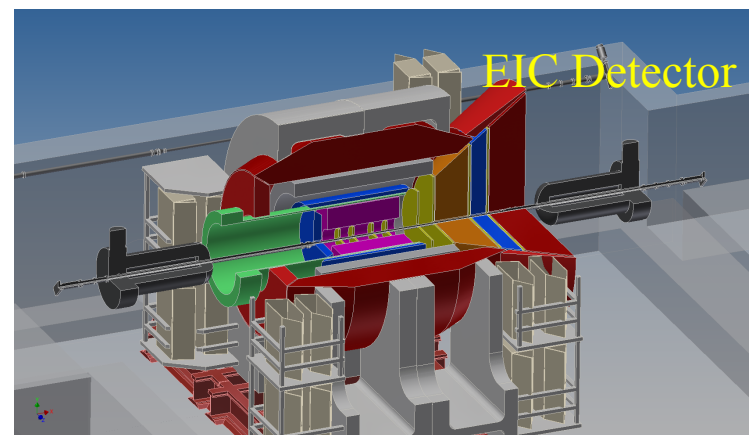
~2021



By ~2025

Evolve sPHENIX (pp and HI detector) to  
EIC Detector (ep and eA detector)

- To utilize e and p (A) beams at eRHIC with e-energy up to 15 GeV and  $p(A)$ -energy up to 250 GeV (100 GeV/n)
- e, p,  $He^3$  polarized
- Stage-1 luminosity  $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  ( $\sim 1 \text{ fb}^{-1} / \text{month}$ )



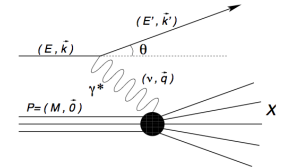


# General Detector Concept

## Inclusive DIS and scattered electron measurements

With focus in e-going direction and barrel

High resolution EMCal and tracking; minimal material budget

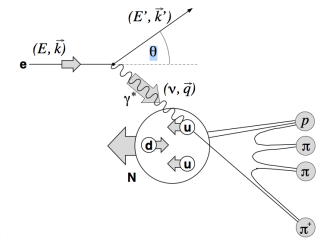


## Semi-inclusive DIS and hadron ID

With focus in h-going direction and barrel

Barrel: DIRC for  $p_h < 4 \text{ GeV}/c$

h-going direction: aerogel for lower  $p_h$  and gas RICH for higher  $p_h$

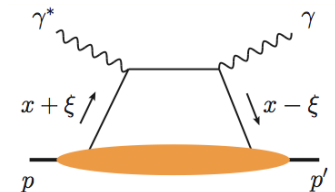


## Exclusive DIS (DVCS etc.)

## EMCal and tracking coverage in $-4 < \eta < 4$

## High granularity EMCal in e-going direction

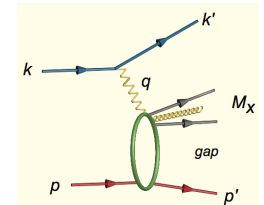
## Roman Pots in h-going direction



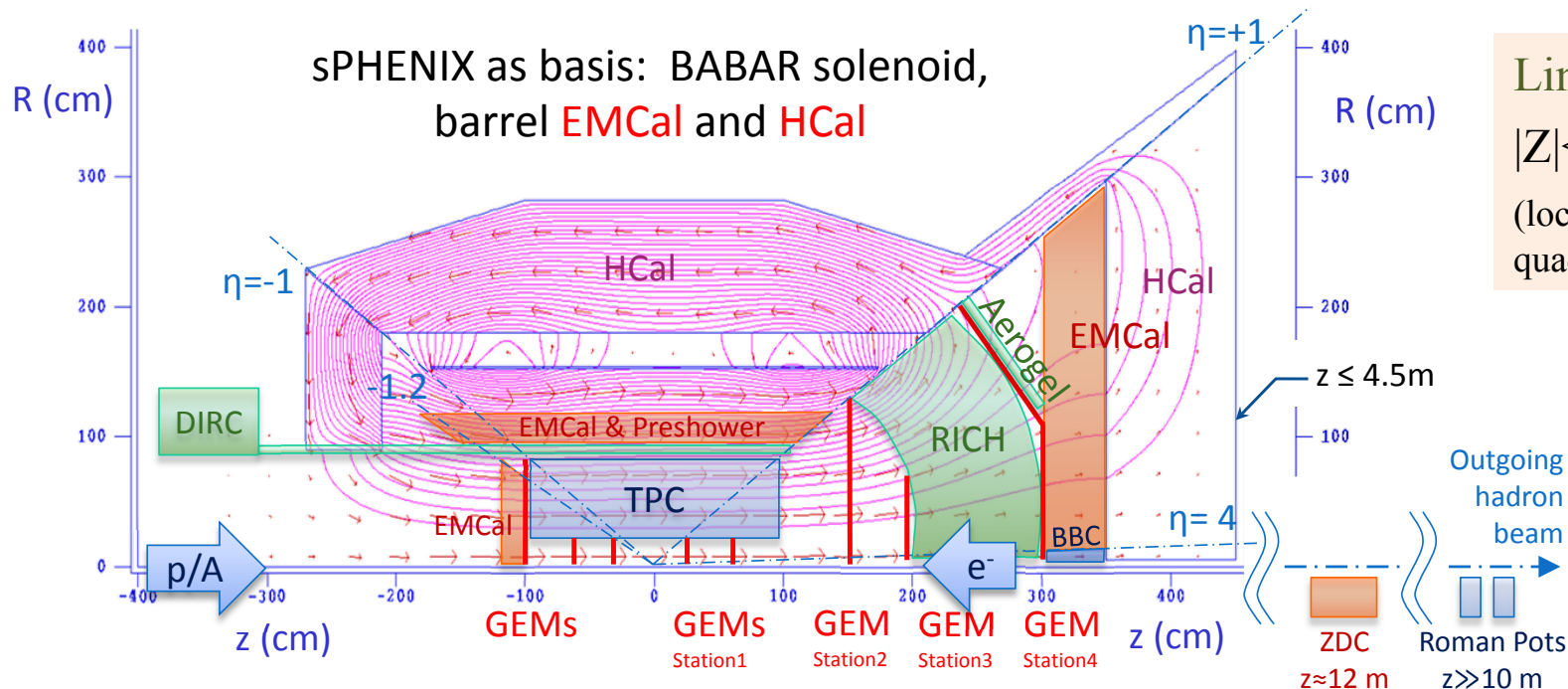
## Diffraction

Rapidity gap measurements: HCal in  $-1 < \eta < 5$ ; EMCal in  $-4 < \eta < 4$

## ZDC in h-going direction



# EIC Detector Proposal



- $-4 < \eta < -1$  (e-going):
  - **Crystal calorimeter** with high energy and position resolution
  - **GEM Trackers**
- $-1 < \eta < 1$  (barrel):
  - Add **Compact-TPC** and **DIRC**
- $1 < \eta < 4$  (h-going):
  - **HCal & EMCAL** ( $1 < \eta < 5$ )
  - **GEM Trackers**
  - **Aerogel RICH** ( $1 < \eta < 2$ )
  - **Gas RICH**
- Far Forward (h-going)
  - **ZDC and Roman Pots**

# BaBar Magnet



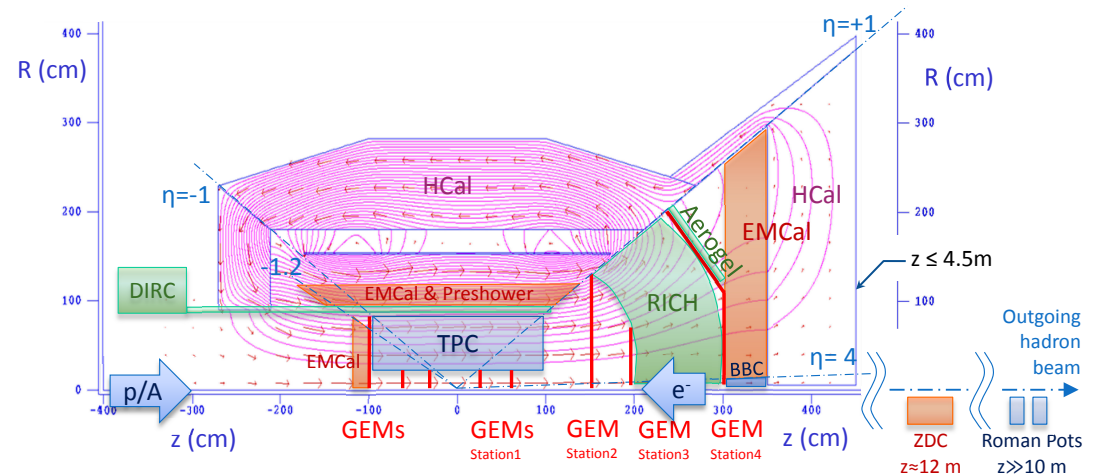
## Major Parameters:

- ✓ Superconducting Solenoid
- ✓ Field: 1.5T
- ✓ Inner radius: 140 cm
- ✓ Outer radius: 173 cm
- ✓ Length: 385 cm

Higher current density at magnet ends and field shaping in forward angles provide **high analyzing power for momentum determination in e-going and h-going directions**

## Flux return and field shaping:

Forward HCal  
Steel lapmshade  
Barrel HCal  
Steel endcup



Main space limitation observed:  $|z| < 4.5\text{m}$   
(due to focusing magnet location)

# Tracking

$$-3 < \eta < 4$$

TPC in barrel ( $15 < r < 80$  cm,  $|z| < 95$  cm)

GEMs in forward and backward

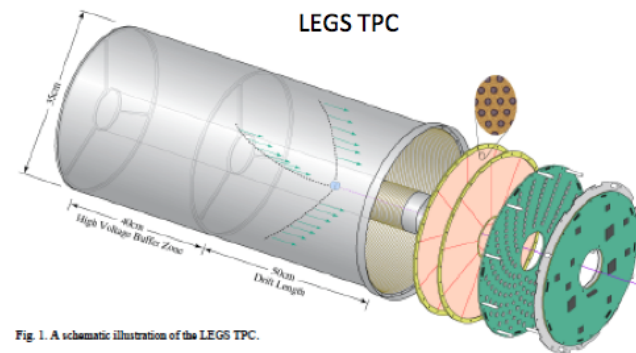
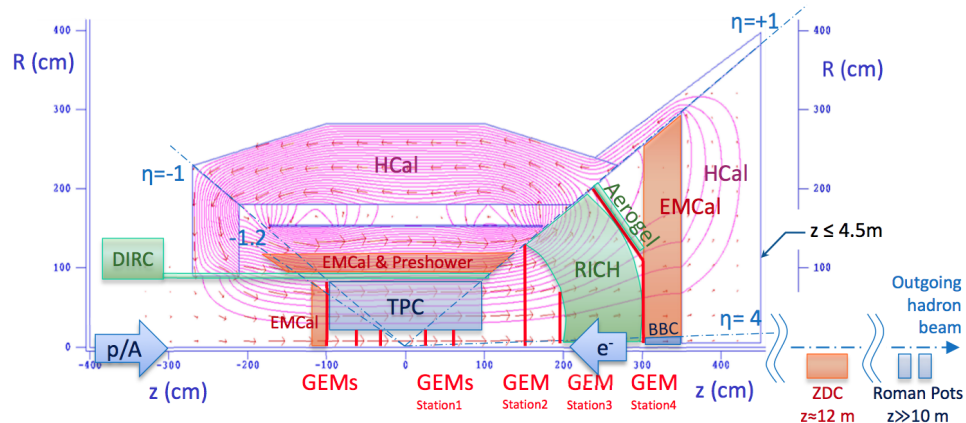
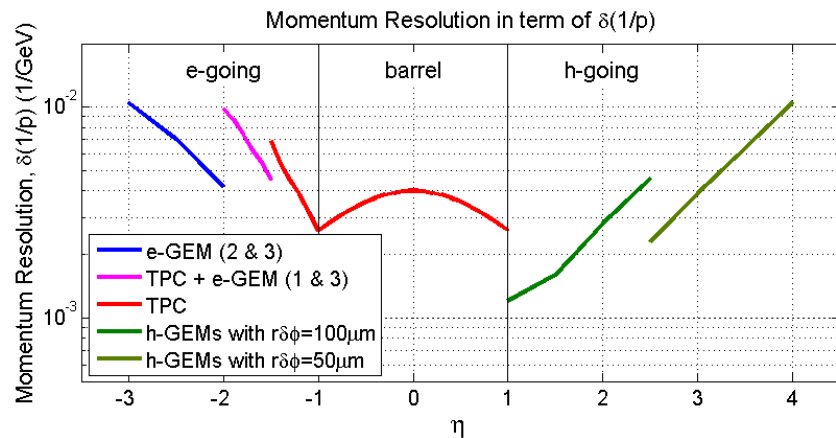


Fig. 1. A schematic illustration of the LEGS TPC.



**Good resolution over full acceptance**

e-going: electron ID ( $E/p$ )

Barrel: low mom. measurements ( $< 10$  GeV/c)

h-going: needed for PID

# EM Calorimetry

$$-4 < \eta < 4$$

Endcap EMCal:

$$\sigma_E/E \sim 1.5\%/\sqrt{E}$$

$$\sigma_X < 3\text{mm}/\sqrt{E}$$

PbWO<sub>4</sub> crystal

Similar to PANDA  
endcap design

Barrel EMCal:

$$\sigma_E/E \sim 12\%/\sqrt{E}$$

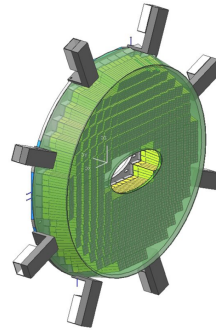
sPHENIX EMCal

Tungsten-fiber

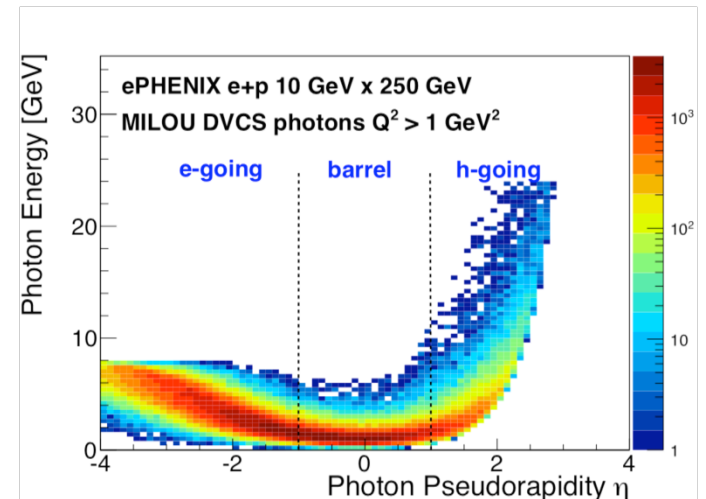
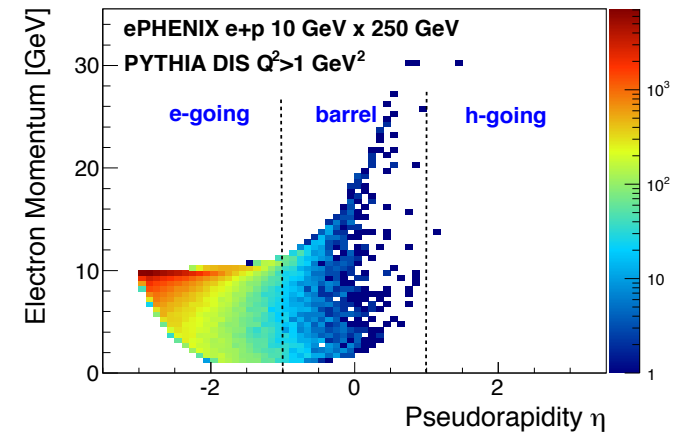
Forward EMCal:

$$\sigma_E/E \sim 12\%/\sqrt{E}$$

Pb-fiber



TDR for PANDA  
arXiv:0810.1216



- Scattered electron measurements
  - High resolutions in e-going direction required
- Vector meson and photon measurements
  - Wide coverage required

# Hadron Calorimetry

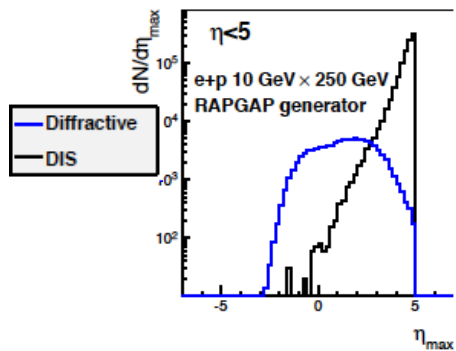
$$-1 < \eta < 5$$

Barrel HCal:

$$\sigma_E/E \sim 100\%/\sqrt{E}$$

Steel & Scintillator

sPHENIX EMCal

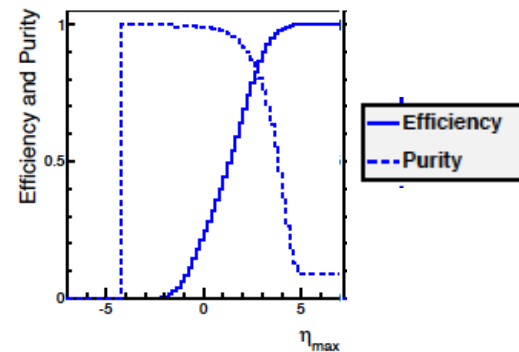


Forward HCal:

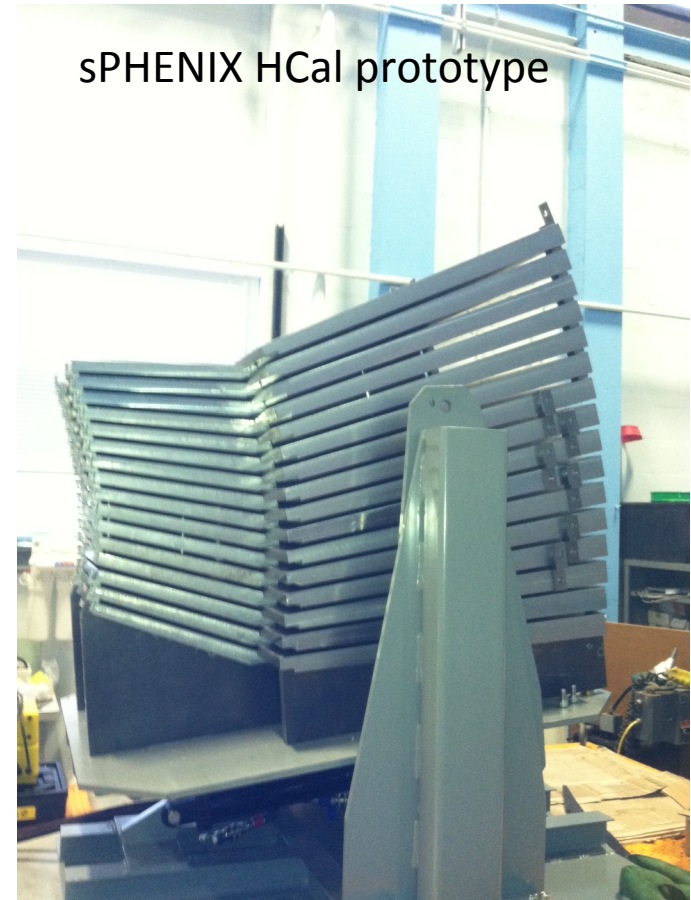
$$\sigma_E/E \sim 100\%/\sqrt{E}$$

Steel & Scintillator

Same as barrel



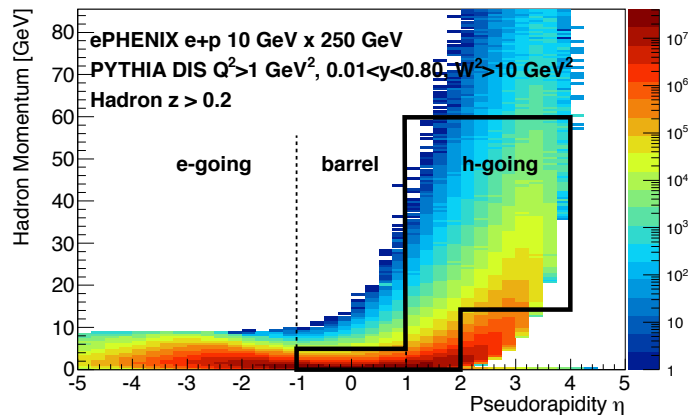
- Rapidity Gap for Diffractive
- Assist to PID and high momentum hadron measurements



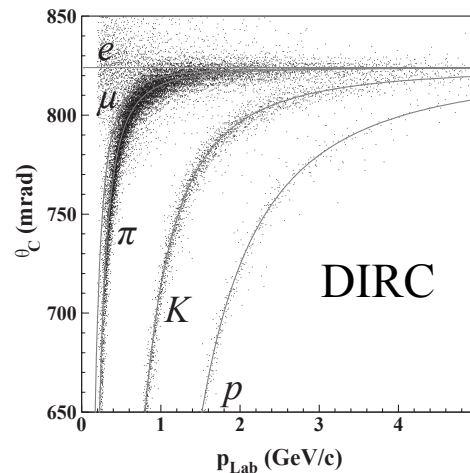


# Hadron PID

$$-1 < \eta < 4$$



Focus on h-going direction and barrel



DIRC:

$$-1 < \eta < 1$$

PID at <4 GeV/c

Aerogel:

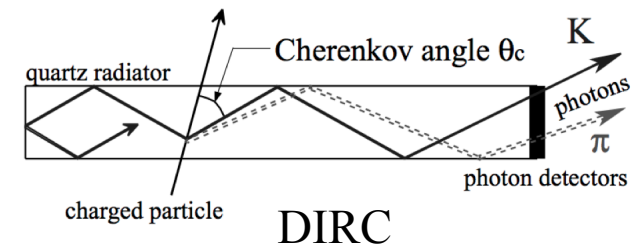
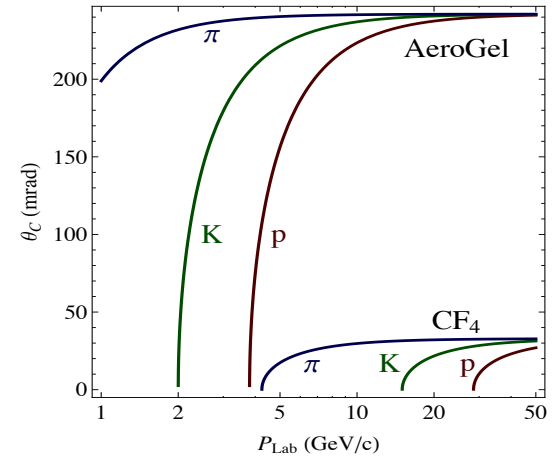
$$1 < \eta < 2$$

PID at <15 GeV/c

Gas RICH (CF<sub>4</sub>):

$$1 < \eta < 4$$

PID at <60 GeV/c



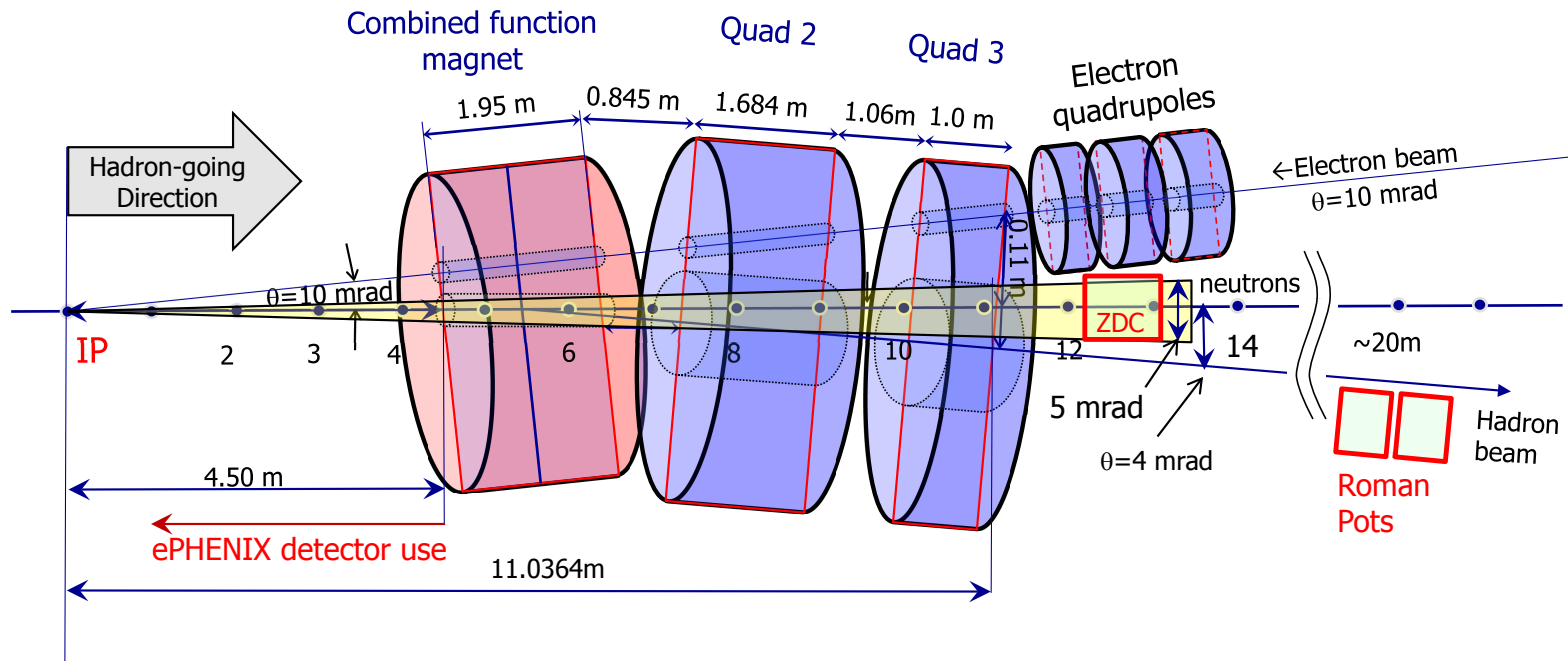
DIRC

## ➤ Quark Helicity, TMDs, Hadronization

Tightly coupled to high resolution momentum measurements in forward

# Beamline Detectors

Similar to all eRHIC detectors, being designed in parallel with IR design



## ZDC

12 m downstream

5 mrad cone opening of the IP is available from ePHENIX and IP design

## Roman Pots

>20 m downstream

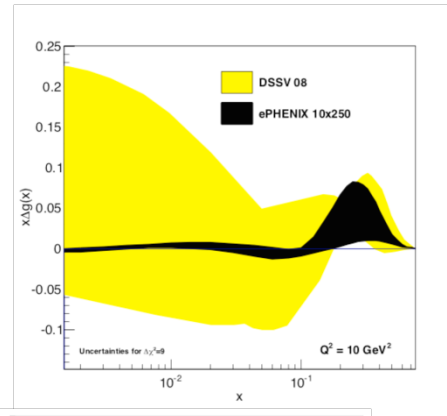
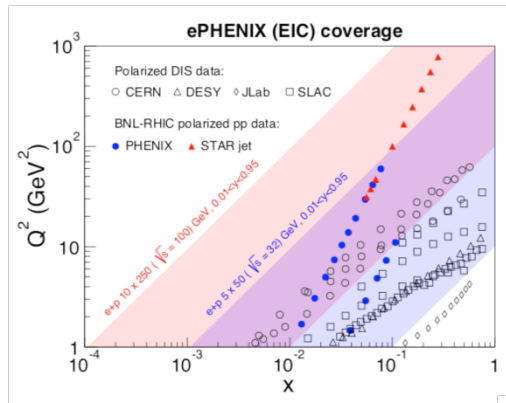
Similar to STAR design

# Physics Expectations

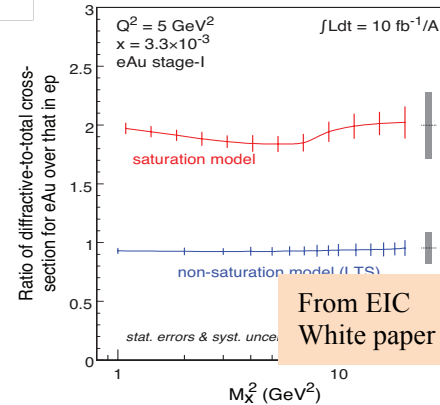
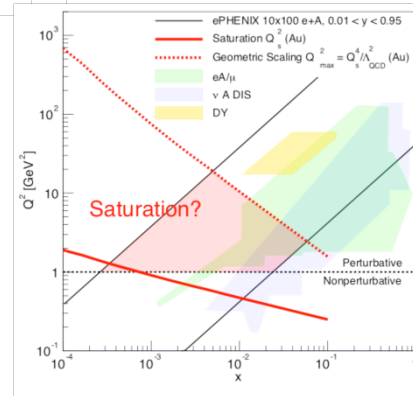
## Proton Helicity Structure

Also:

TMD (motion of confined partons)  
GPD (Proton tomography)



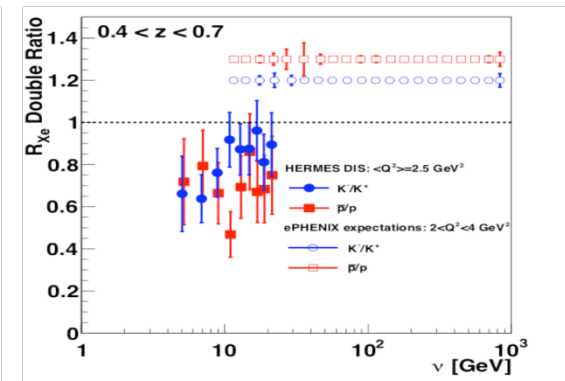
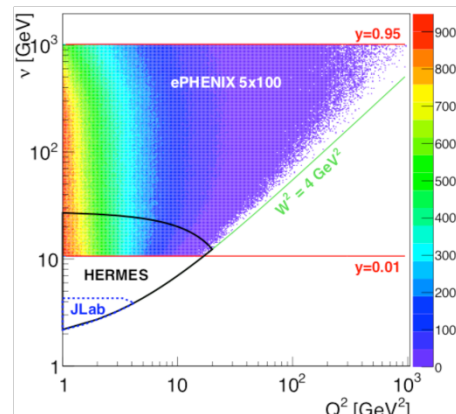
Gluon  
saturation



From EIC  
White paper

$$Q_s^2(x) \propto \left(\frac{A}{x}\right)^{1/3}$$

Propagation and  
hadronization



# Summary

PHENIX → sPHENIX (2021) → EIC Detector (2025)

- sPHENIX Science and Cost&Schedule Review in July 2014
- EIC Detector Concept Review, Jan 10, 2014

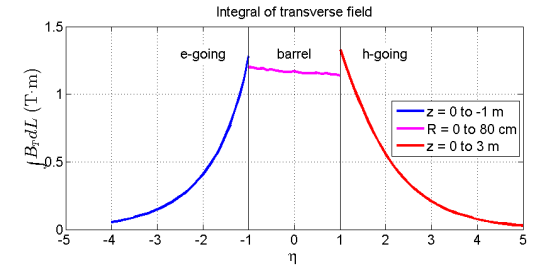
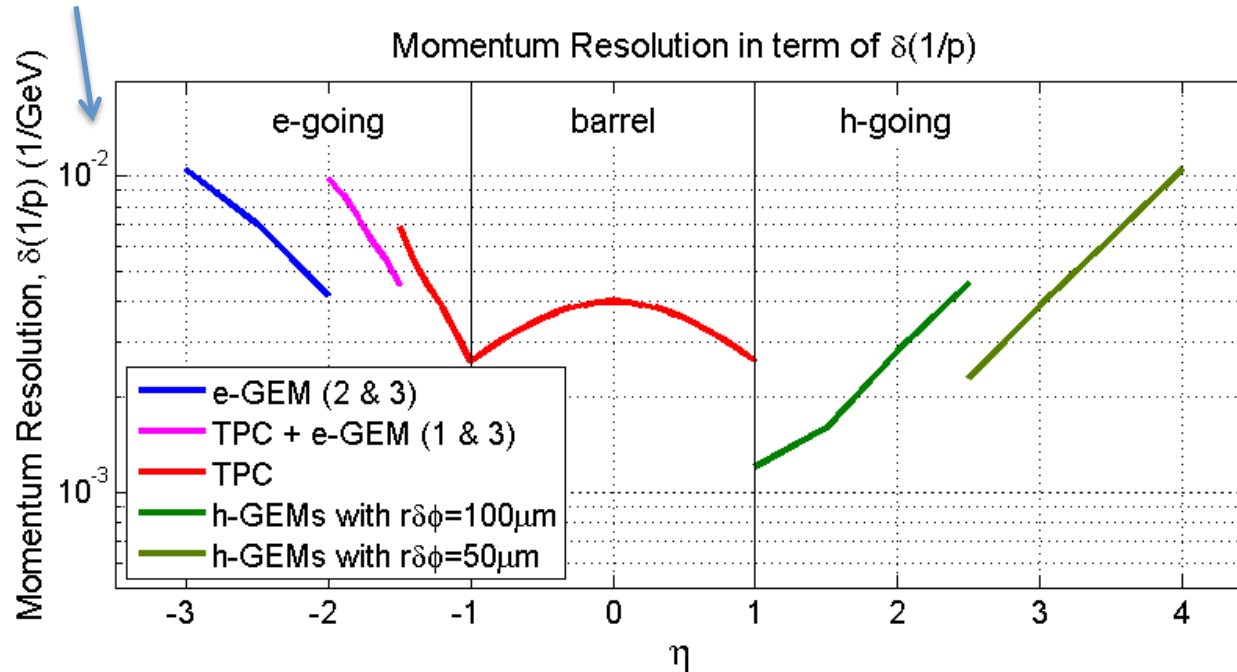
Proposed EIC Detector is a comprehensive detector to address a broad range of EIC physics

- Summarized in Letter of Intent: [arXiv:1402.1209](#)
- To be evolved from sPHENIX → sPHENIX upgrade is consistent with EIC detector plans
- New collaboration to be formed with a lot of opportunities in detector design, physics program development and scientific leadership

# Backup

# Momentum Resolution

$$\delta p/p \sim a \times p$$

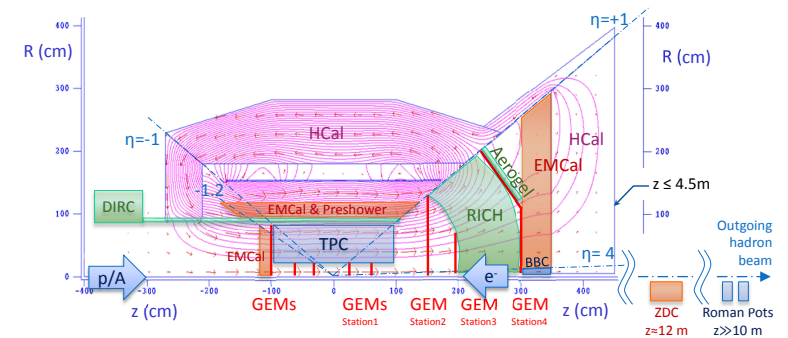


Good resolution over full tracking acceptance ( $-3 < \eta < 4$ ):

e-going,  $\sigma_p/p \sim (0.4-1.0\%) \times p$ : primarily needed for electron ID ( $E/p$ )

barrel,  $\sigma_p/p < 0.4\% \times p$ : hadron momentum, electron momentum at  $p < 10 \text{ GeV}/c$

h-going,  $\sigma_p/p \sim (0.1-1.0\%) \times p$ : crucial for PID





# Inclusive DIS and Kinematics

## Resolutions for $(x, Q^2)$

$$\frac{\sigma_{Q^2}}{Q^2} = \frac{\sigma_{E'}}{E'} \quad \frac{\sigma_x}{x} = \frac{1}{y} \frac{\sigma_{E'}}{E'}$$

Angle resolution provided by EMCal position resolution doesn't affect  $(x, Q^2)$  resolution

Defines the precision of unfolding technique to correct for smearing due to detector effects

Results in statistics migration from bin to bin  
→ bin survival probability

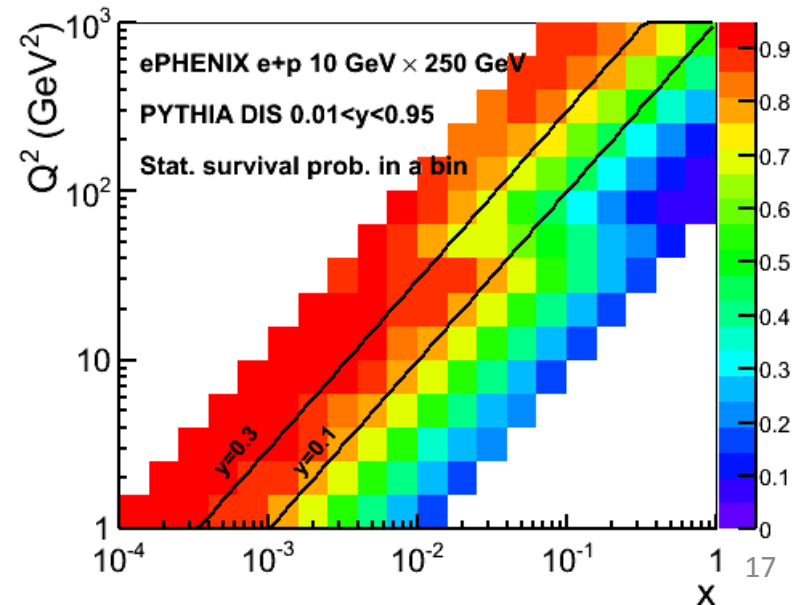
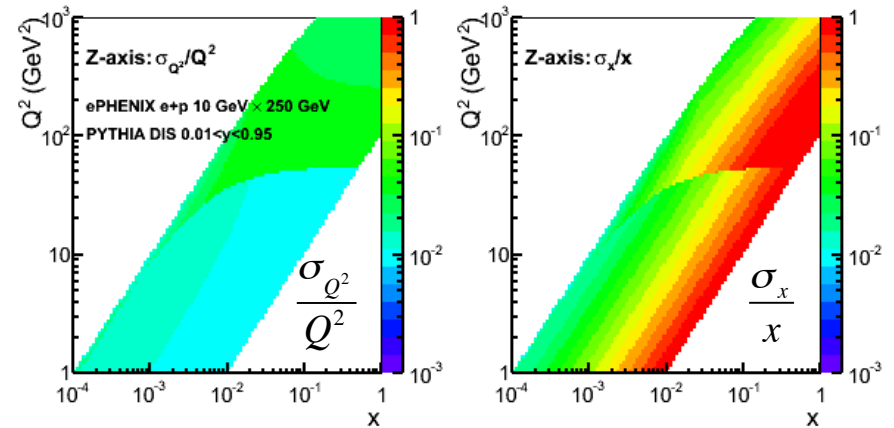
From HERMES experience: ~80% needed

Jacquet-Blondel method (with hadronic final state) will help at lower  $y$  and higher  $Q^2$

Bremsstrahlung radiation: no sizable effect

Minimal material

GEANT4: 3-7% impurity for  $y=0.5-0.95$



# Inclusive DIS and Kinematics

## eID and background rejection

### Hadron rejection:

EMCal energy response and E/p

×20-30 at 1 GeV/c

×100 at 3 GeV/c

EMCal shower profile

Expect ×3-10

Not yet included in plots

EMCal long. segmentation and/or  
preshower

For future considerations

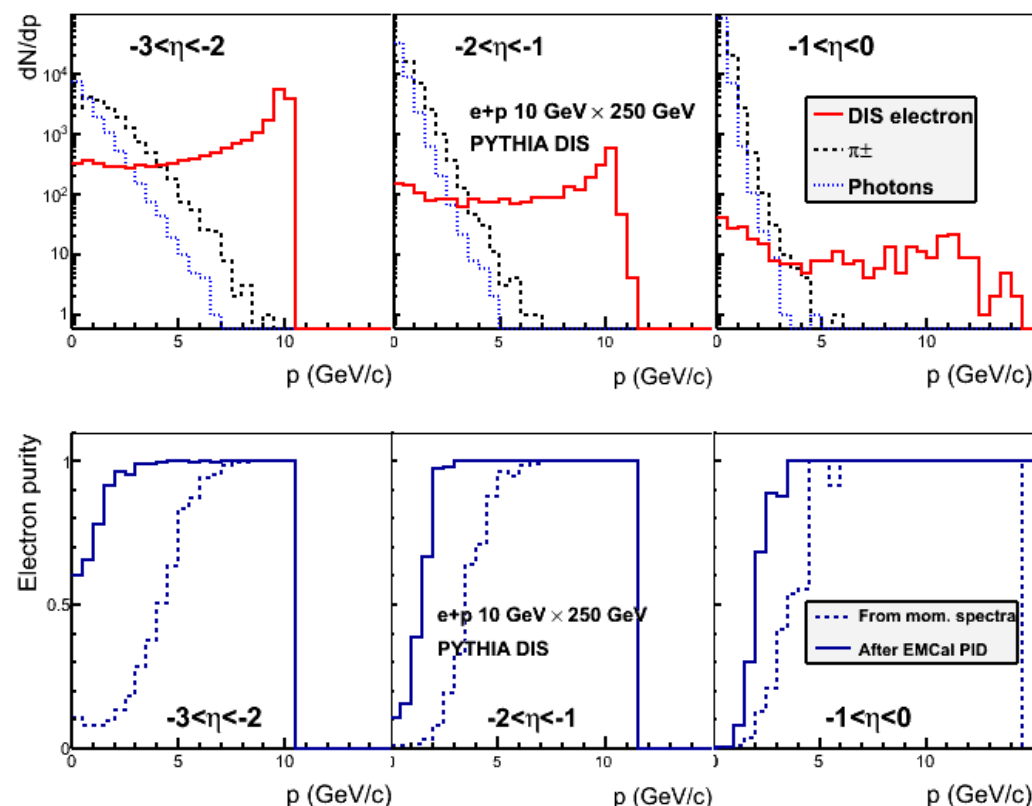
### Photon rejection ( $\gamma \rightarrow e^+e^-$ )

Minimal material

GEANT4 studies:

>3 GeV/c: background negligible

<3 GeV/c: rejected with tracking+EMCal



Reliable eID down to

p=2 GeV/c for 10 GeV e-beam

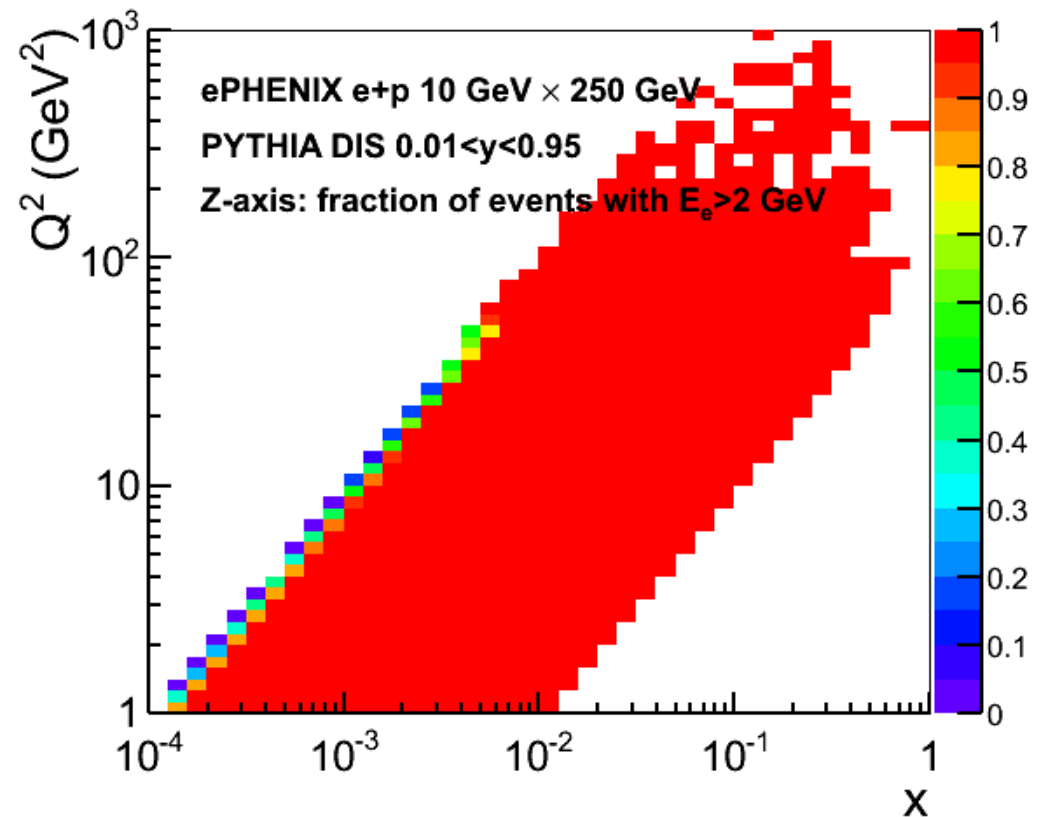
p=1 GeV/c for 5 GeV e-beam

Negligible effect on the probed ( $x, Q^2$ ) space

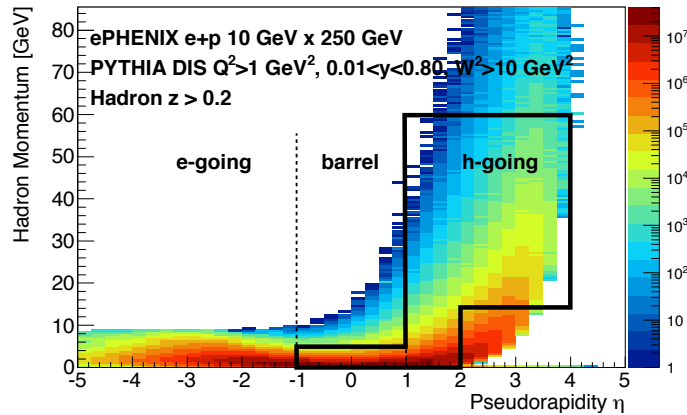
# Inclusive DIS and Kinematics

What if poor eID at  $< 2 \text{ GeV}/c$

Don't lose much of  
the  $(x, Q^2)$  space



# Hadron ID with gas RICH

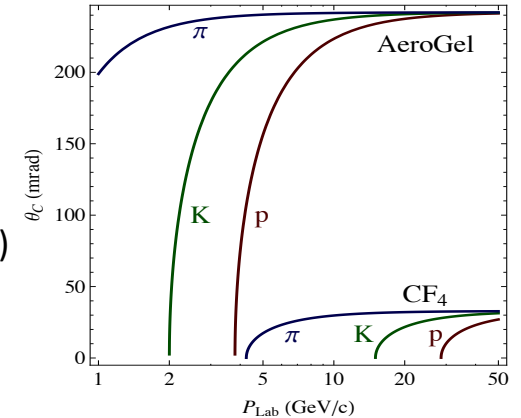


## Gas RICH (CF<sub>4</sub>): $1 < \eta < 4$

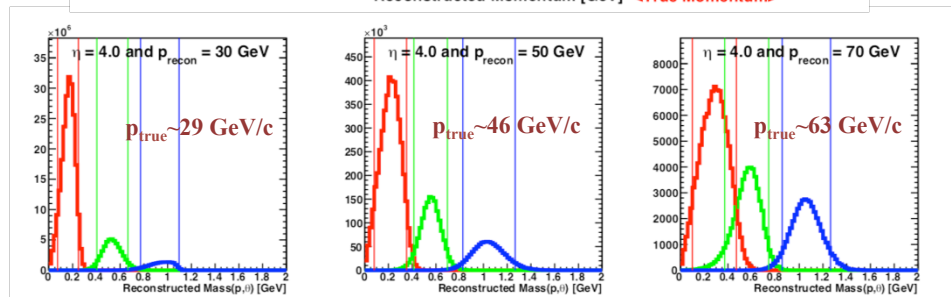
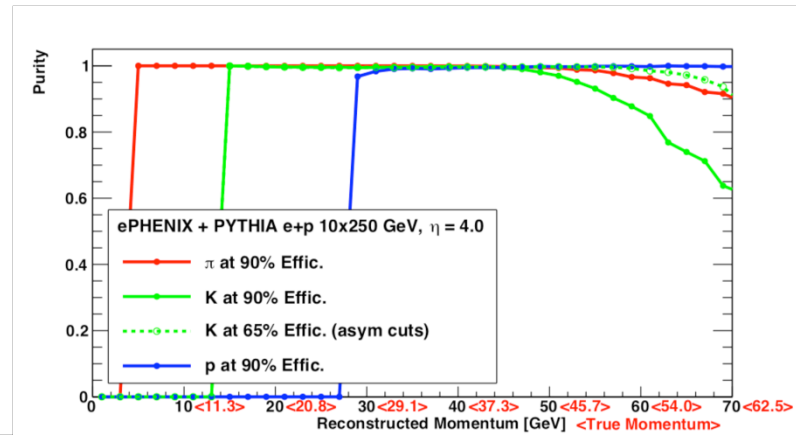
Highest momentum measurements require:

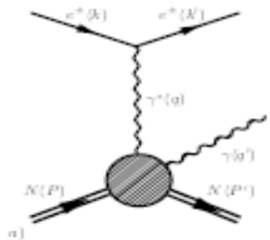
- Good momentum resolution (combination of tracking and HCal)
- Good ring resolution

Need to balance efficiency and purity to get best measurement



- PID up to  $\sim 60$  GeV/c
- Currently limited by ring resolution (2.5% per photon - the current feedback from EIC R&D)
- Much smaller smearing due to magnetic field and off-center-vertex tracks





# Exclusive Measurements

## DVCS:

Wide coverage for photon measurements

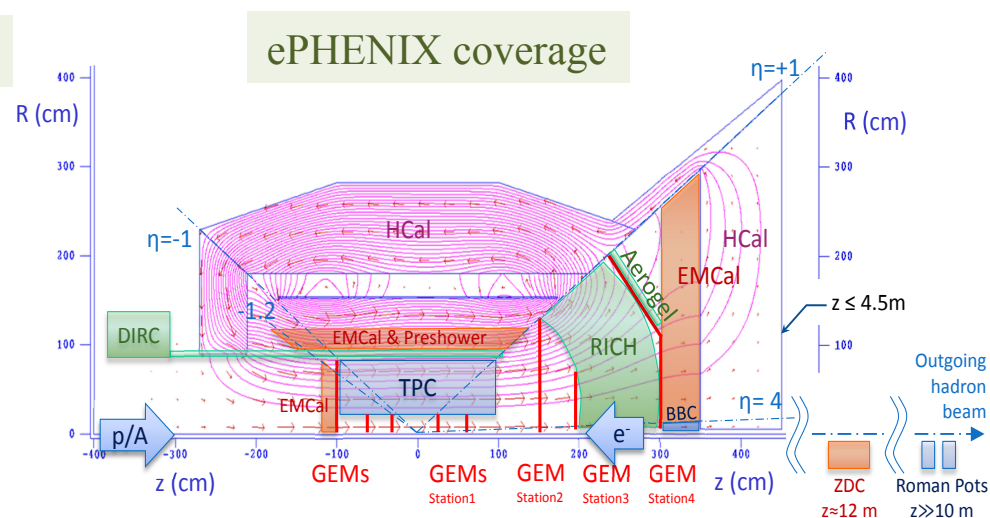
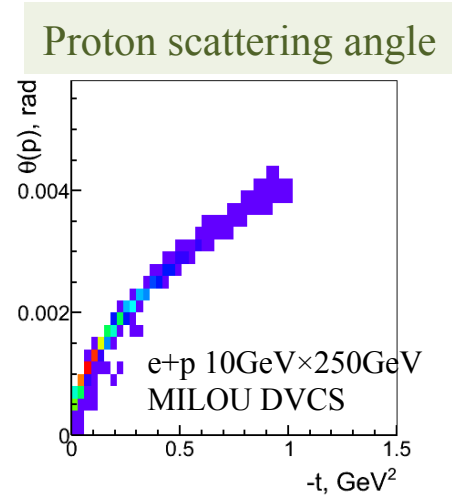
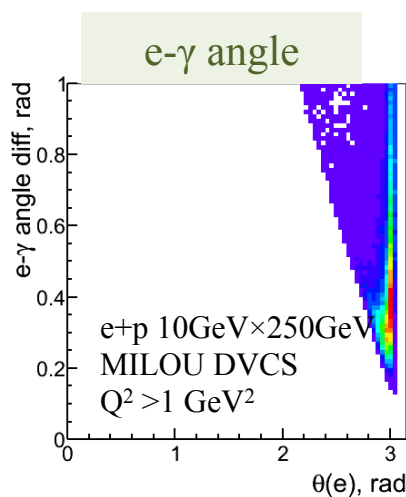
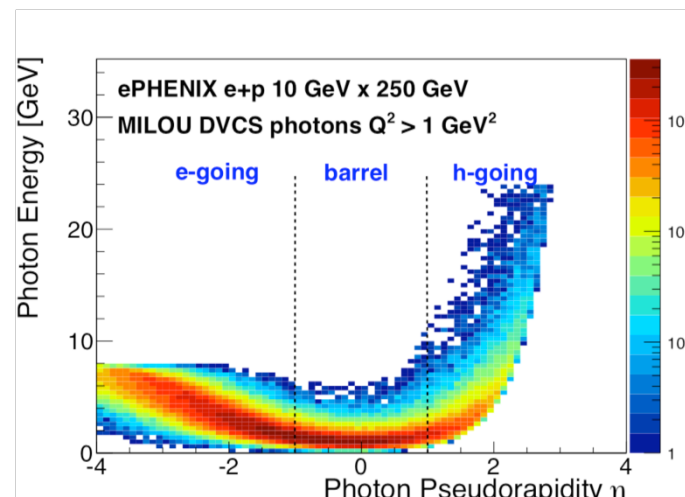
EMCal and tracking in  $|\eta| < 4$

Separation of  $e$ - $\gamma$  in EMCal

$0.02 \times 0.02$  EMCal granularity is sufficient

Intact proton detection is highly desirable

Roman Pots

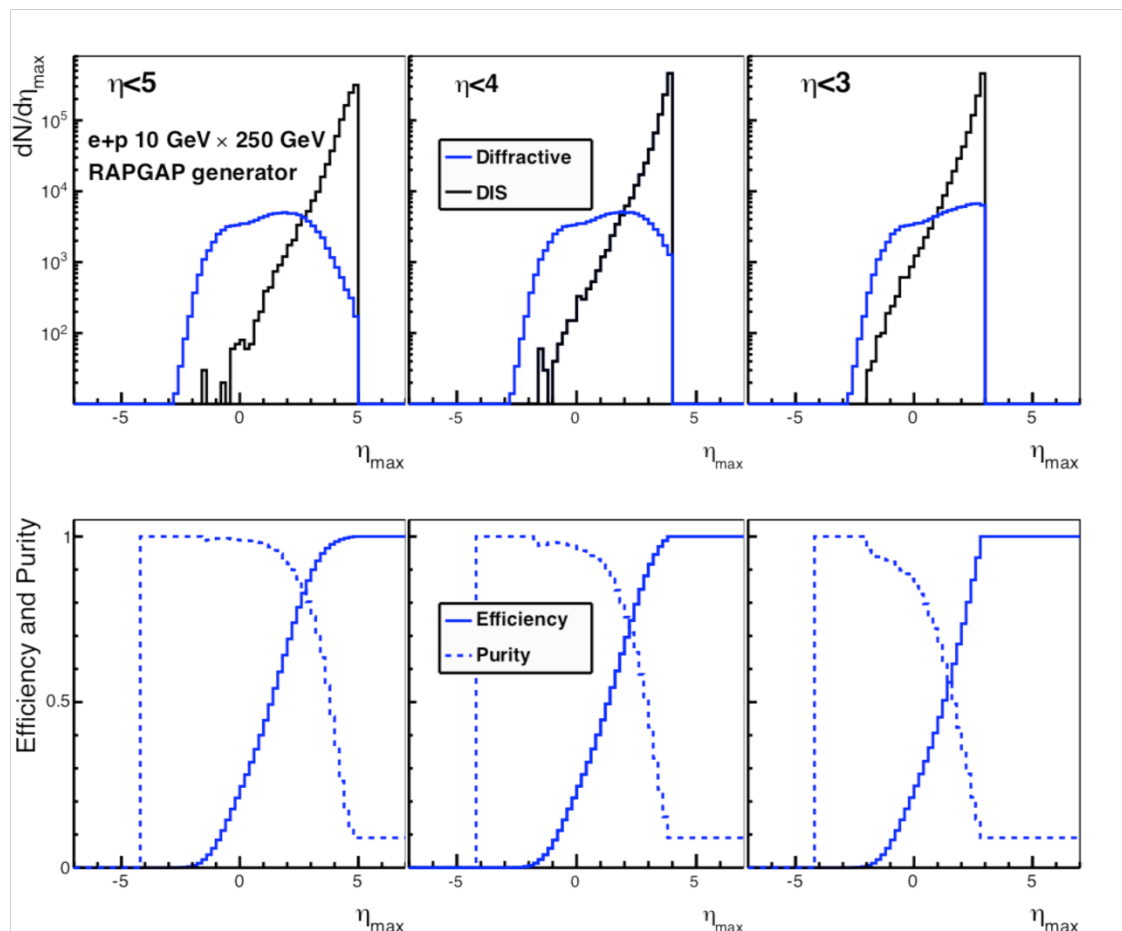


# Diffraction Measurements

- Measure most forward going particle, to determine rapidity gap

HCal with  $-1 < \eta < 5$  and  
EMCal with  $-4 < \eta < 4$  are  
excellent in separation of  
DIS and diffractive

- ZDC to measure nucleus  
breakup





# TPC

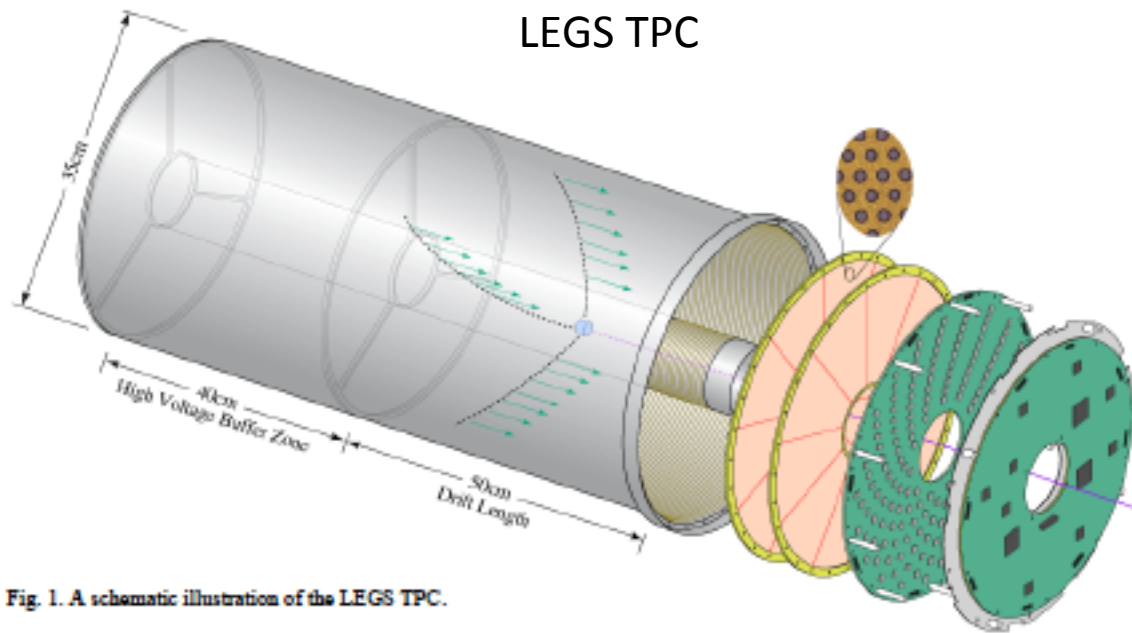
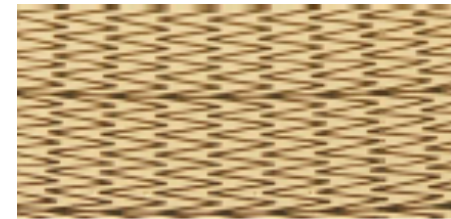


Fig. 1. A schematic illustration of the LEGS TPC.

Chevron-type readout pattern with a pad size 2mm × 5mm

Achieved pos. res. 200  $\mu\text{m}$



## ePHENIX TPC:

$R=15\text{-}80\text{cm}$ ,  $|z|<95\text{cm}$

Gas mixture with fast drift time: 80% Ar, 10% CF<sub>4</sub>, 10% CO<sub>2</sub>

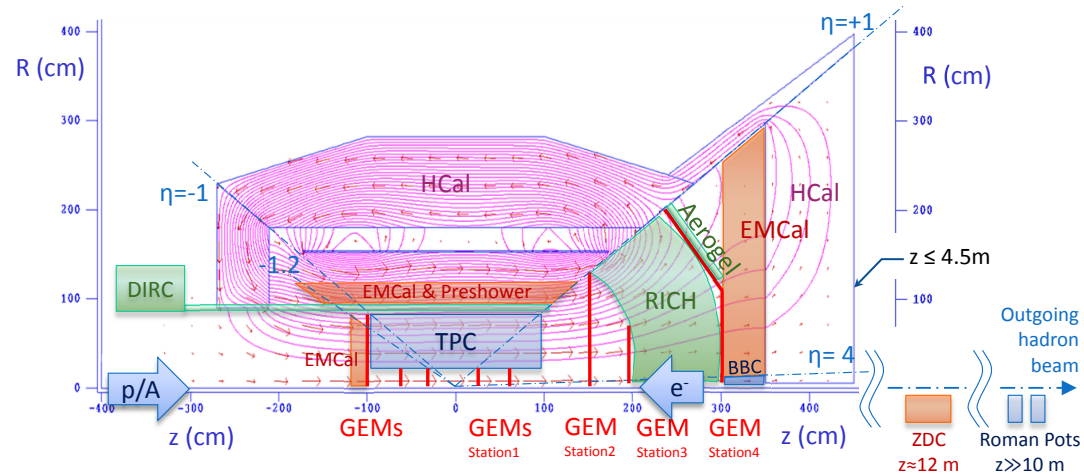
For 650 V/m  $\rightarrow$  10cm/ $\mu\text{s}$   $\rightarrow$  Drift time 10  $\mu\text{s}$

2×10mm pads  $\rightarrow$  180k pads (both ends readout)

Pos. resolution 300  $\mu\text{m}$  (twice longer drift distance than LEGS)  
and 40 readout rows  $\Rightarrow \sigma_p/p \sim 0.4\% \times p$

# Tracking with GEM

Improved pos. res.  
with mini-drift GEM



## e-going direction

Station 1-2:  $z=30, 55\text{cm}$   $r=2-15\text{cm}$

Station 3:  $z=98\text{ cm}$

$-3 < \eta < -2$ :  $50\mu\text{m}$  with  $1\text{mm}$  pad

$-2 < \eta < -1$ :  $100\mu\text{m}$  with  $2\text{mm}$  pad

$\Delta r=1\text{cm}$  for St1-2 and  $\Delta r=10\text{cm}$  for St3

## h-going direction

Station 1:  $z=17$  and  $60\text{cm}$  with  $r=2-15\text{cm}$

Station 2-4:  $z=150, 200, 300\text{ cm}$ ,  $1 < \eta < 4$

$2.5 < \eta < 4$ :  $50\mu\text{m}$  with  $1\text{mm}$  pad

$1 < \eta < 2.5$ :  $100\mu\text{m}$  with  $2\text{mm}$  pad

$\Delta r=1-10\text{cm}$

Collision vertex is necessary in e-going direction:

BBC:  $\eta=4-5$ ,  $z=3\text{m}$ ,  $\sigma_t=30\text{ps}$  (with MRPC or MCP)  $\rightarrow$   
 $\sigma_z=5\text{mm}$   $\rightarrow$  const term in  $\sigma_p/p \sim 2\%$

Total channel count: 217k

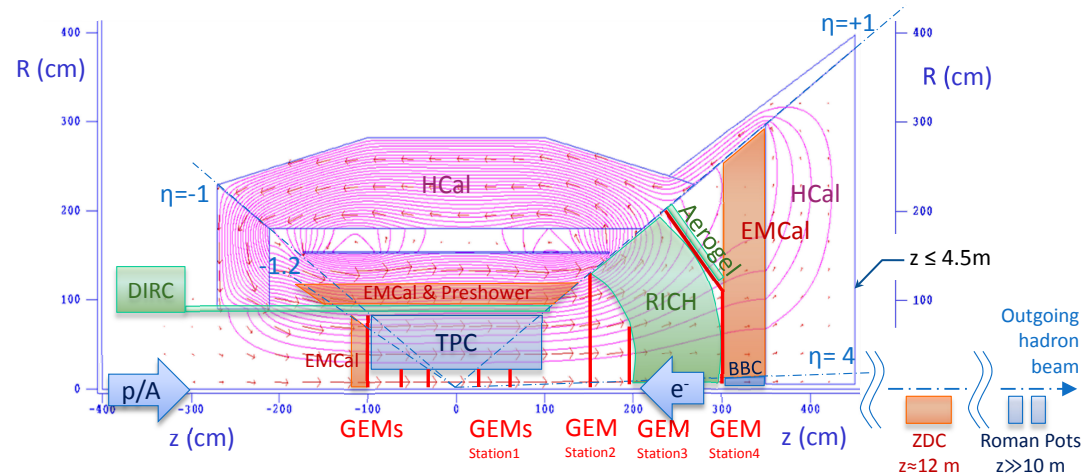
Large area GEMs are being  
developed in CERN for CMS  
(needed for our St 2-4)

# Calorimetry

EMCal coverage  $-4 < \eta < 4$

HCal coverage  $-1 < \eta < 5$

Readout: SiPM



## e-going direction

### Crystall EMCal:

2cm×2cm

5k towers

$\sigma_E/E \sim 1.5\%/\sqrt{E}$

$\sigma_x \sim 3\text{mm}/\sqrt{E}$

## Barrel (sPHENIX)

### Tungsten-fiber EMCal:

2cm×2cm

25k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

### Steel-Sc HCal:

10cm×10cm

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

## h-going direction

### Pb-fiber EMCal:

3cm×3cm

26k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

### Steel-Sc HCal:

10cm×10cm

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

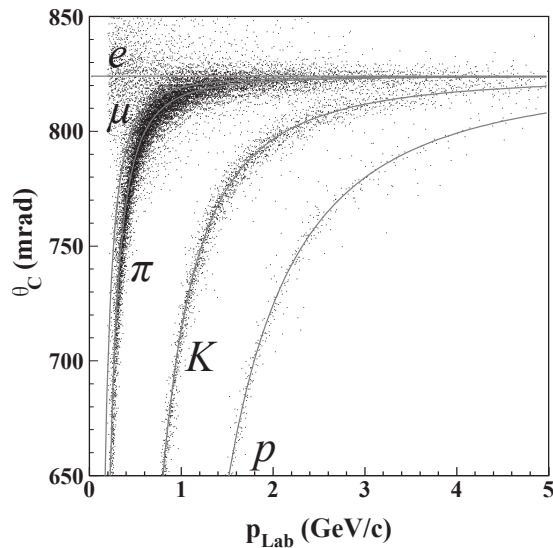
# Hadron PID

## DIRC

$$-1 < \eta < 1$$

Mirror focusing

Threshold for  $\pi/K/p$ :  
0.2/0.7/1.5 GeV



## Gas RICH (CF4)

$$1 < \eta < 4$$

Mirror focusing

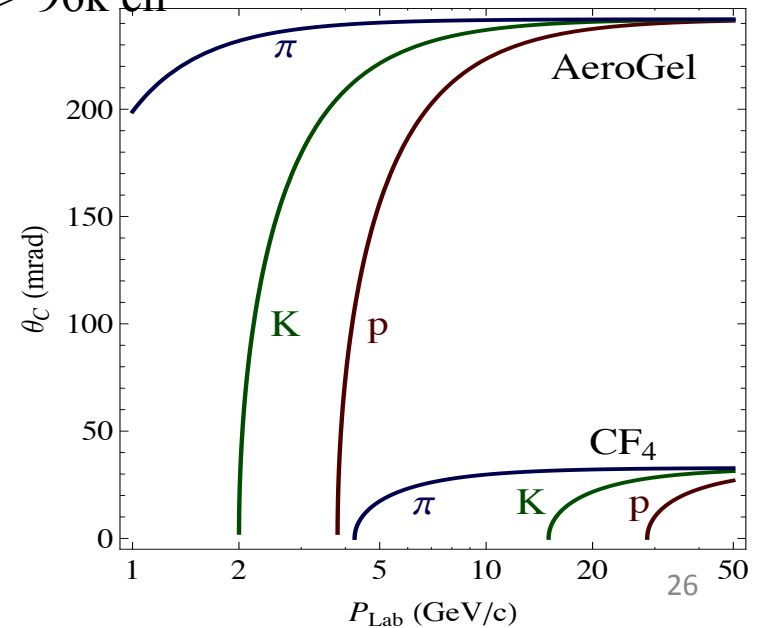
Threshold for  $\pi/K/p$ :  
4/15/29 GeV

6 azimuthal segments

Photodetection: GEM with CsI

Area  $6 \times 0.3 \text{ m}^2 \rightarrow 96 \text{ k ch}$

In gas volume!



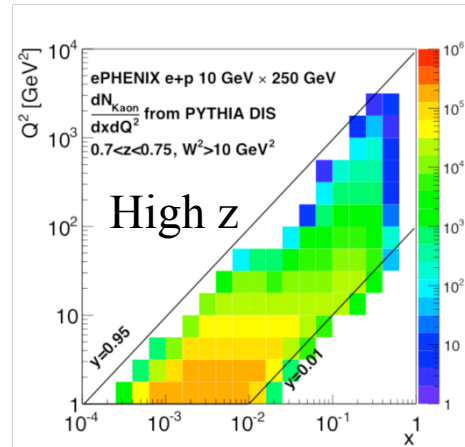
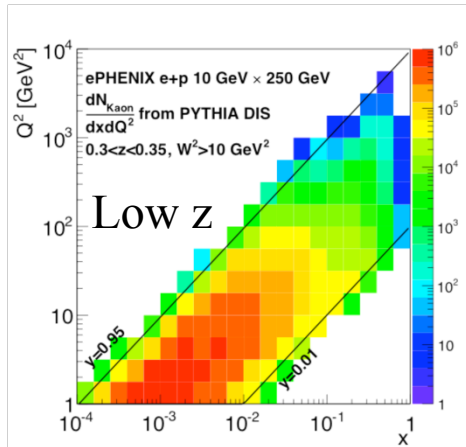
## Aerogel

$$1 < \eta < 2$$

Proximity focused

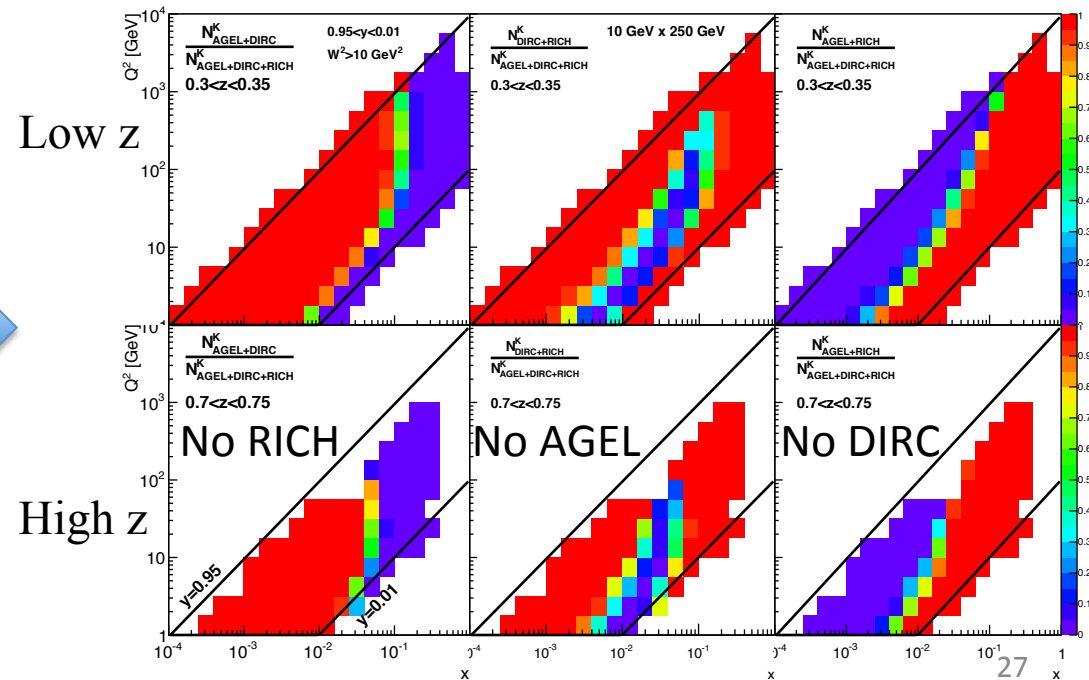
Threshold for  $\pi/K/p$ :  
0.6/2/4 GeV

# Semi-inclusive DIS and hadron ID



←  $(x, Q^2)$  coverage with K

$(x, Q^2)$  loss if not have given detector



All three detectors are important

# Hadron PID: gas RICH

CF4 ( $n=1.00062$ )

## Ring resolution

Ring radius resolution:  $2.5\%/\sqrt{N_\gamma}$

From current EIC R&D studies

LHCb and COMPASS claimed 1%  
per photon

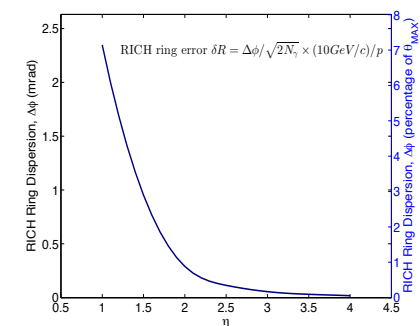
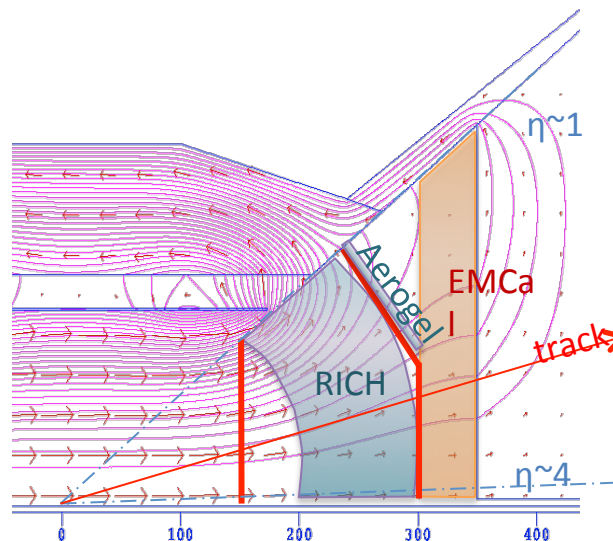
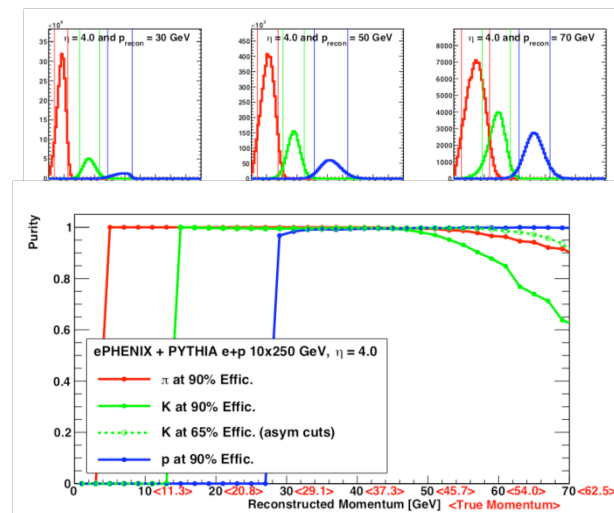
Residual magnetic field ( $\sim 0.5$  T)  
bends tracks radiating photons  $\Rightarrow$  ring  
smearing

Since field is near parallel to tracks  
the effect is minimal

Off-center vertex tracks have shifted  
focal plane  $\Rightarrow$  ring smearing

For  $\eta=1$  and  $z=40\text{cm}$   $\Rightarrow$  ring  
dispersion  $5\%/\sqrt{N_\gamma} \times (10 \text{ GeV}/c) / p$

For larger  $\eta$  effect is smaller



Ring resolution limits PID at higher p



# Hadron measurements with HCal and Tracking

At very forward rapidity ( $\eta \sim 4$ ) HCal energy resolution for single tracks may considerably exceed tracking momentum resolution

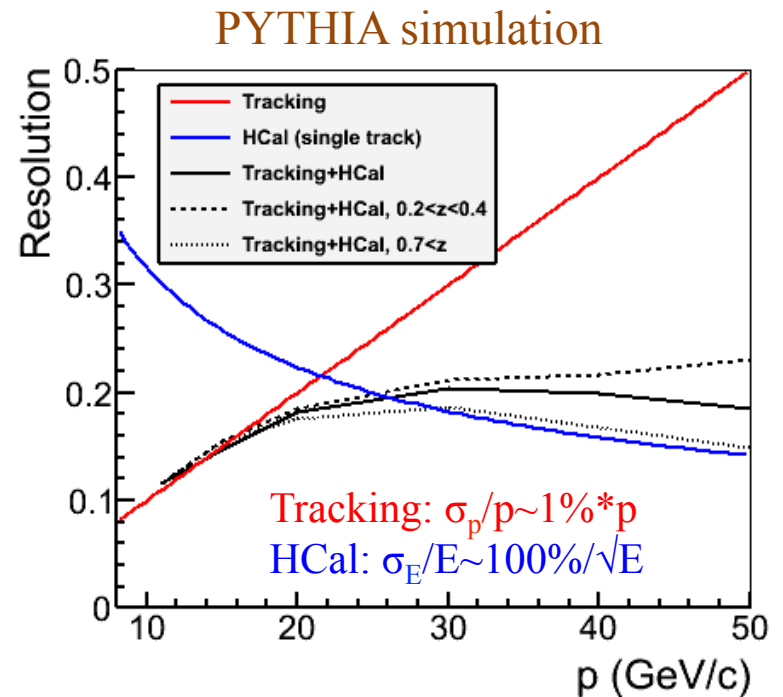
Can HCal be used to measure energy (momentum) of high momentum tracks ?

The main concern is that the energy depositions of tracks in vicinity of a given track are merged in a single cluster in HCal (non-separable in HCal)

The idea:

Usual event structure is that there is one high momentum leading particle with a few lower momentum particles;

Low momentum particles are supposed to be well reconstructed with tracking, so their contribution in HCal can be evaluated and subtracted to calculate the energy deposition of the leading high momentum particle.



Full GEANT4 simulation is ongoing  
The main impact is expected from tracking eff. and ghost (high momentum) tracks

# Hadron PID: Aerogel

Allows to identify K for  $3 < p < 10$  GeV

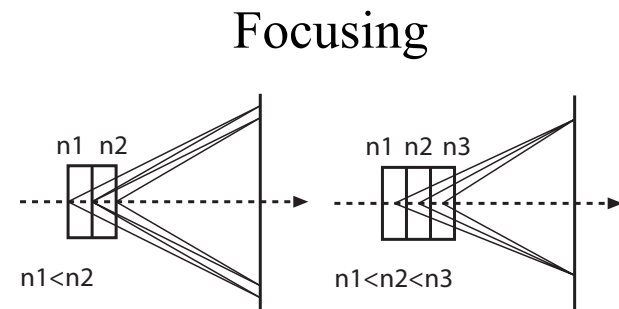
## Challenges:

Fringe field

Low light output

Visible wavelength range

Limited space for light focusing



Photon detection:

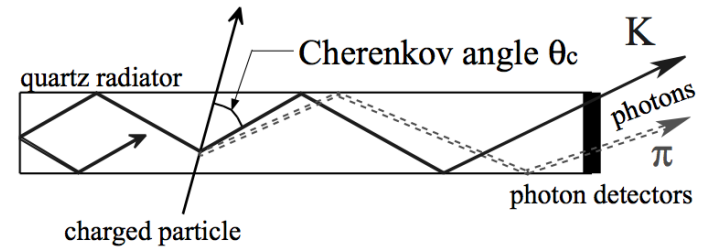
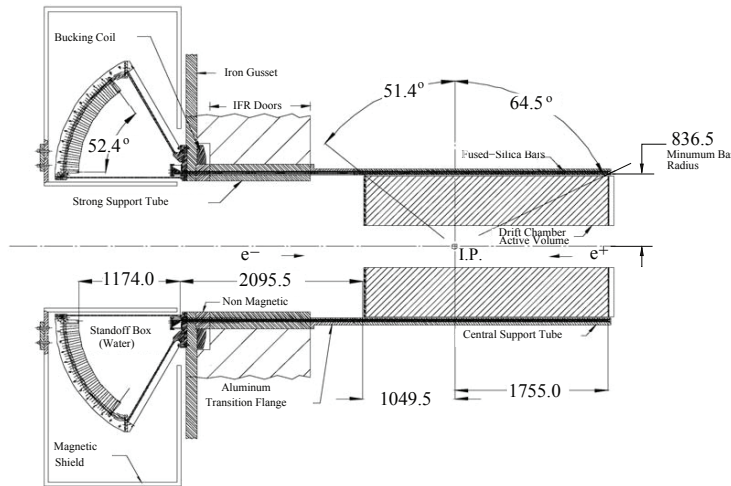
Microchannel Plate Detector

Multi-alkali photocathode

Also ToF with  $\sigma = 20\text{-}30\text{ps}$

Being developed by  
LAPPD Collaboration

# Hadron PID: DIRC



## BaBar DIRC

Quartz radiator bars, Cerenkov  
light internally reflected

No focusing  $\Rightarrow$  Large water filled  
expansion volume

PMT for readout

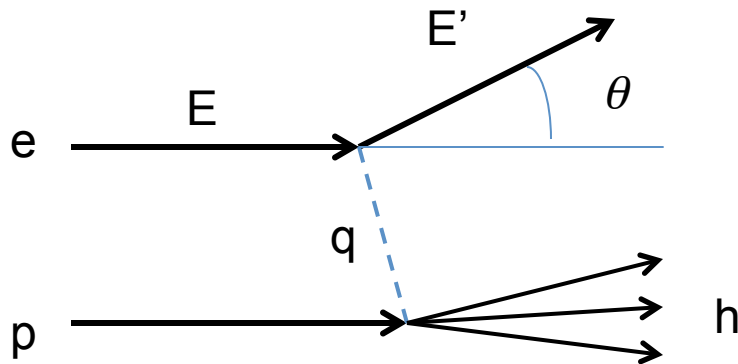
## ePHENIX DIRC

Mirror Focusing to avoid large  
expansion region

Pixelated multi-anode PMT for  
readout

Ring resolution limits PID at higher p

# Electron vs Jacquet-Blondel



Electron

$$Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E} \cos^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

$$y \rightarrow 0: \sigma_y/y \sim 1/y$$

JB

$$Q_{JB}^2 = \frac{p_{T,h}^2}{1 - y_{JB}}$$

$$y_{JB} = \frac{(E - p_z)_h}{2E_e}$$

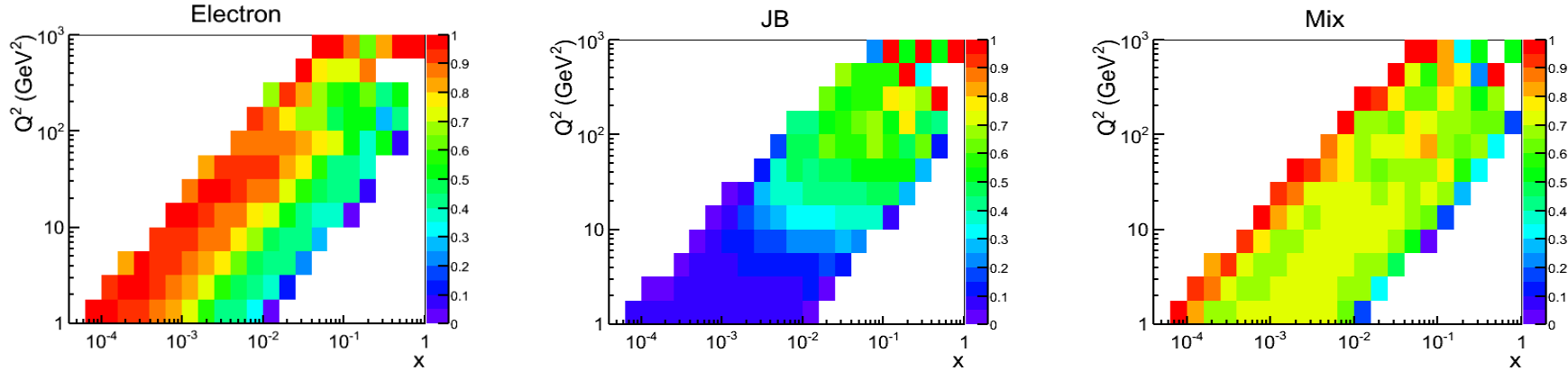
$$x_{JB} = \frac{Q_{JB}^2}{sy_{JB}}$$

$$p_{T,h}^2 = \left( \sum_h p_{x,h} \right)^2 + \left( \sum_h p_{y,h} \right)^2$$

$$(E - p_z)_h = \sum_h (E_h - p_{z,h})$$

$$y \rightarrow 0: \sigma_y/y \sim \text{const}$$

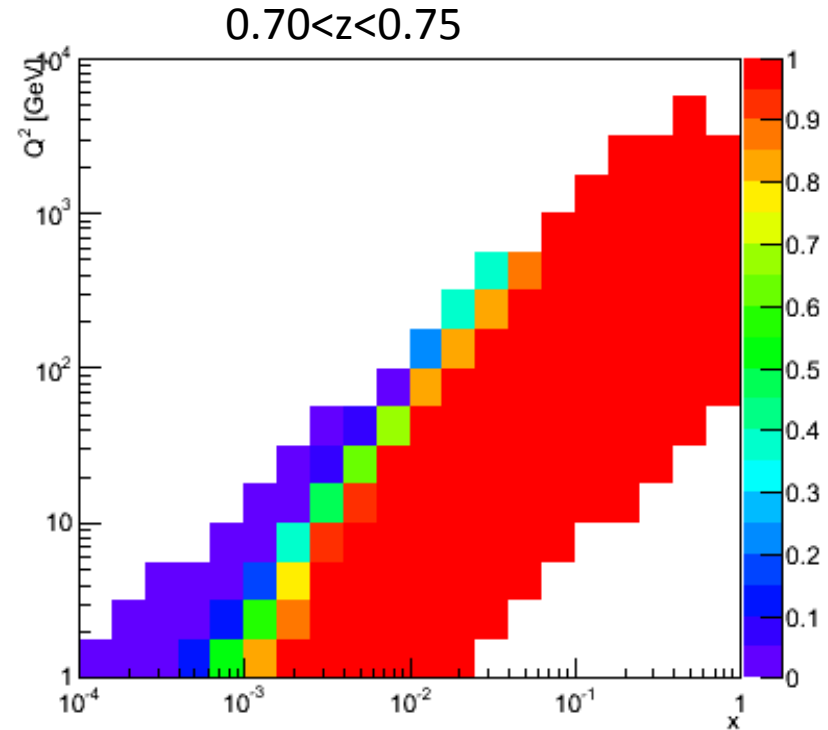
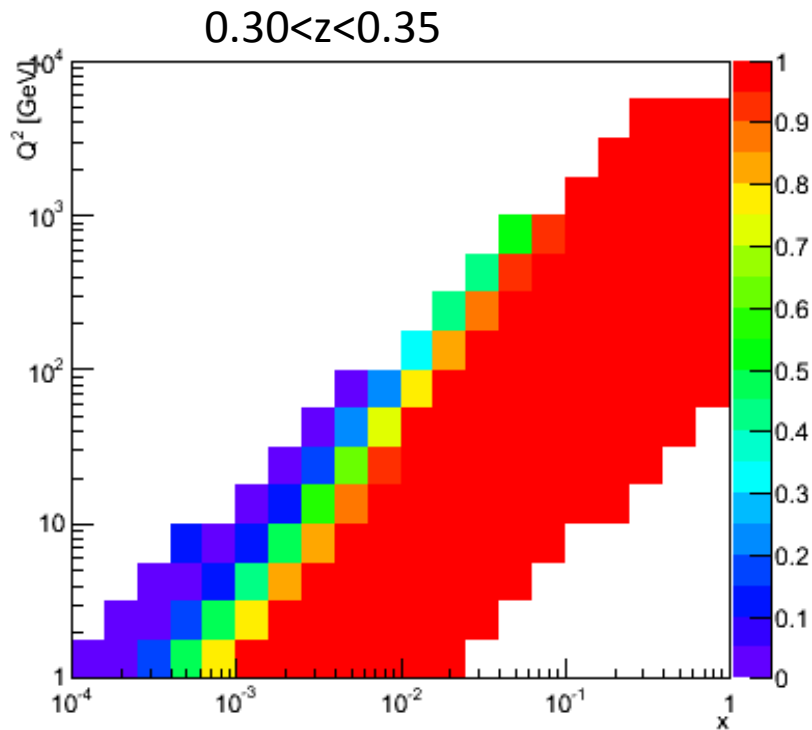
# Electron vs JB vs Mix



For 15 GeV  $\times$  250 GeV beam energy configuration, event purity in  $(x, Q^2)$  bins, defined by the likelihood of an event to remain in its true  $(x, Q^2)$  bin after resolutions smearing; left – for electron method, middle – for Jacquet-Blondel method, and right – for “Mixed” method, when  $Q^2$  is defined from electron method,  $y$  is defined from Jacquet-Blondel method, and  $x=Q^2/(sy)$ .

# $(x, Q^2)$ loss due to no ePID in e-going direction

e+p 10 GeV  $\times$  250 GeV  
PYTHIA DIS  $0.01 < y < 0.95$   $W^2 > 10 \text{ GeV}^2$



# If better DIRC?

e+p 10 GeV  $\times$  250 GeV  
PYTHIA DIS  $0.01 < y < 0.95$   $W^2 > 10 \text{ GeV}^2$

“Normal” DIRC: pi/K separation up to 3.5 GeV/c  
Improved DIRC: pi/K separation up to 6 GeV/c

